29th EPS Conference on Plasma Phys. and Contr. Fusion Montreux, 17-21 June 2002 ECA Vol. **26B**, P-1.107 (2002)

Resistive wall mode studies in the EXTRAP T2R reversed-field pinch

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Introduction

A close, perfectly conducting shell provides wall stabilisation for MHD modes in the reversed-field pinch (RFP). However, a real shell with finite conductivity cannot stabilise the MHD mode. Instead it converts the mode into a resistive wall mode (RWM) which grows on the time scale of flux penetration through the shell [1]. The dominating m=1 resonant modes in the RFP are mainly current driven resistive-MHD modes, which are often rotating modes. If the typical plasma rotation frequency exceeds the inverse shell time constant, the thin shell behaves effectively as an ideal shell for these modes. A rotating RFP plasma is indeed expected to be unstable mainly to non-resonant, non-rotating m=1 RWMs. The MHD unstable m=1 modes of a RFP can be separated into groups based on the sign of the toroidal mode number n: *Internally* resonant and non-resonant m=1,$n<0$ modes have the same helicity handedness as the equilibrium field *inside* the reversal radius. *Externally* resonant and non-resonant m=1, $n>0$ modes have the same helicity handedness as the equilibrium field *outside* the reversal radius.

The growth rates of RWMs have been measured in the EXTRAP T2R thin shell RFP device. The experimental growth rates for both internal and external RWMs are in reasonable agreement with linear MHD stability calculations.

Characteristics of the EXTRAP T2R device

The EXTRAP T2R reversed field pinch [2] has a major radius R=1.24 m. The plasma limiter minor radius is a=0.183 m. The radius of the thin shell is r_w=0.198 m giving a shell proximity of r_w/a=1.08. The vertical field penetration time of the shell is τ_{ver}=6.3 ms. The shell time constant is intermediate in the sense that it is longer than the RFP setting up time, but shorter than the discharge pulse length. The typical global parameters of the T2R device (plasma current I_p=100 kA, toroidal loop voltage V_t=30 V) are similar to those of thick shell RFP devices of the same size. The pulse lengths in this study are typically in the range 12-22 ms which are 2 -3 times longer than the shell time constant. The internally resonant modes exhibit spontaneous fast rotation, which thereby suppresses the associated radial magnetic field perturbation at the wall [3]. The equilibrium and the internal mode dynamics are not noticebly affected by the thin shell in EXTRAP T2R even though the pulse length significantly exceeds the shell time.

Magnetic diagnostics

An array of 256 B_r-flux loops distributed at 4 poloidal and 64 toroidal positions is installed on the outer vessel surface of EXTRAP T2R for measurement of MHD mode activity. The flux loops are situated outside the vacuum vessel at a radius of r=0.197 m, inside the thin shell. The loops have one single turn and span a poloidal angle of 360/4=90 degrees and a toroidal angle of 360/64=5.125 degrees, thus fully covering the vessel surface.

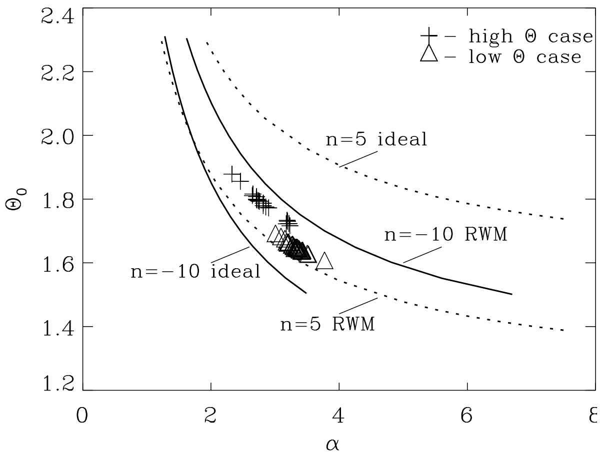

Fig. 1. Ideal MHD and RWM stability boundaries for an internal (m=1, n=-10) and a typical external (m=1, n=5) mode in (Θ_0, α) space. Experimental data show equilibrium points for a low-Θ case and a high-Θ case.

For the present study a set of 128 coils at 4 poloidal and 32 toroidal positions are used. This allows the decomposition of the B_r perturbation at the shell into Fourier modes with poloidal mode number m=0,1 and toroidal mode number $-16<n<16$, which is adequate for the RWM study. The coil signals are time-integrated using active integrators.

Equilibrium magnetic field profiles

The equilibrium magnetic field profiles are modelled with the Θ_0–α model, which uses an expression for the profile of the normalised parallel currrent density profile as follows: $j_{||}(r)/B(r)=(2\Theta_0/\mu_0 a)(1-(r/a)^{\alpha})$ [4]. The parallel current density profile is characterised by the two parameters Θ_0 and α, which experimentally are obtained from measurements of the pinch parameter $\Theta=B_\theta(a)/<B_\phi>$ and the reversal parameter $F=B_\phi(a)/<B_\phi>$. In the estimation of Θ_0 and α a fixed pressure profile has been assumed, described by the expression $p(r)/(B(0)^2/2\mu_0)=\beta_0(1-(r/a)^{\gamma})^2$ with $\beta_0=0.06$ and $\gamma=4$. This corresponds to a poloidal beta in the range β_{pol}=0.15-0.20, (increasing with Θ). Two discharge types have been studied in this investigation; a low-Θ equilibrium and a high-Θ equilibrium. The low-Θ case is characterised by shot averaged equilibrium parameter values Θ=1.64 and F=–0.14, which correspond to current density profile parameters θ_0=1.60 and α=3.73. For low Θ, the Θ and F values are relatively stationary. On the other hand, for the high-Θ case, sawtooth-like oscillations in Θ and F are observed. For an assumed fixed pressure profile, the equilibrium point moves in Θ_0–α space during the sawtooth cycle, entering the ideal MHD unstable region before the sawtooth crash. In this case, the low-Θ point in the sawtooth cycle, which corresponds to an ideal MHD stable equilibrium, is used for the RWM stability study. The high-Θ case is characterised by shot averaged equilibrium parameter values Θ=1.84 and F=–0.38, corresponding to θ_0=1.68 and α=3.52.

Linear MHD calculations of RWM instabilities

The measurements are compared with the predictions of linear MHD theory. The theoretical analysis follows the method outlined in Refs [5,6]. A cylindrical, zero pressure model is used with parallel current density profile described by the experimental values for Θ_0 and α. A vacuum region between the plasma and the resistive wall given by $r_w=1.08a$ is used, in correspondence with the actual position of the thin shell in EXTRAP T2R. The RWM growth rates are normalised to the long time constant of the wall $\tau_w=\mu_0\sigma d r_w=13.8$ ms.

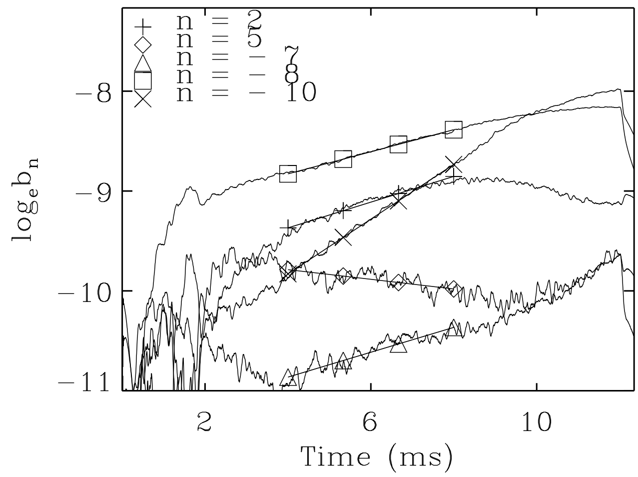

Fig. 2: Time evolution of mode amplitudes for several non-resonant RWM modes. Growth rates are estimated by exponential fitting during the sustainment phase (4-8 ms).

The ideal MHD stability boundary curves and resistive wall mode stability boundary curves in (Θ_0 , α) space for an internal *(m=1, n=−10)* and a typical external *(m=1, n=5)* RWM mode are shown in Fig.1. The ideal MHD boundary is computed assuming an ideal wall at the position of the thin shell. The RWM stability boundary is given by the ideal MHD stability boundary for the ideal wall position at infinity. For the internal modes the stable region in (Θ_0 , α) space is above and to the right of the curves. For the external modes, the stable region is below and to the left of the curves. The region of RWM instability for each mode is between the ideal MHD boundary and the RWM boundary. The experimental equilibria are close to the ideal MHD boundary for internal modes, which is determined by the modes resonant near the axis. Near the internal ideal stability boundary, high growth rates are expected for the internal resistive wall modes that are just non-resonant or resonant near the axis, the so called "on-axis" RWMs. The experimental magnetic equilibria are generally quite far from the ideal boundary for external modes.

Estimates of experimental growth rates and comparison with theory

The time evolution of some dominant non-resonant *m*=1 modes are shown in Fig.2. Two phases of the discharge can be observed. First, there is a turbulent setting-up phase with high fluctuating mode amplitudes. Then, during the sustainment phase, the mode amplitude fluctuation level is smaller, and a steady growth of the non-resonant modes are observed. The experimental estimate of the growth rate is done by performing an exponential fit to the mode amplitude during the time interval 4-8 ms in the sustainment phase, in which period the Θ and *F* values are approximately constant. During this period, the non-resonant modes grow exponentially in time, indicating that the mode amplitudes are in the linear regime, permitting a direct comparison with linear MHD theory. In Fig. 3, shot averages of experimental growth rates for modes $-16<n<16$ are compared with theoretical growth rates for the low-Θ and the high-Θ cases. For the experimental growth rates, only modes which have good exponential fits (with positive growth rates) are included. A threshold value of the χ^2- value for the fit is used as selection criterion. Mainly some modes with higher $|n|>11$, that have a fluctuating mode amplitude or clearly non-exponential or negative growth are excluded by this method.

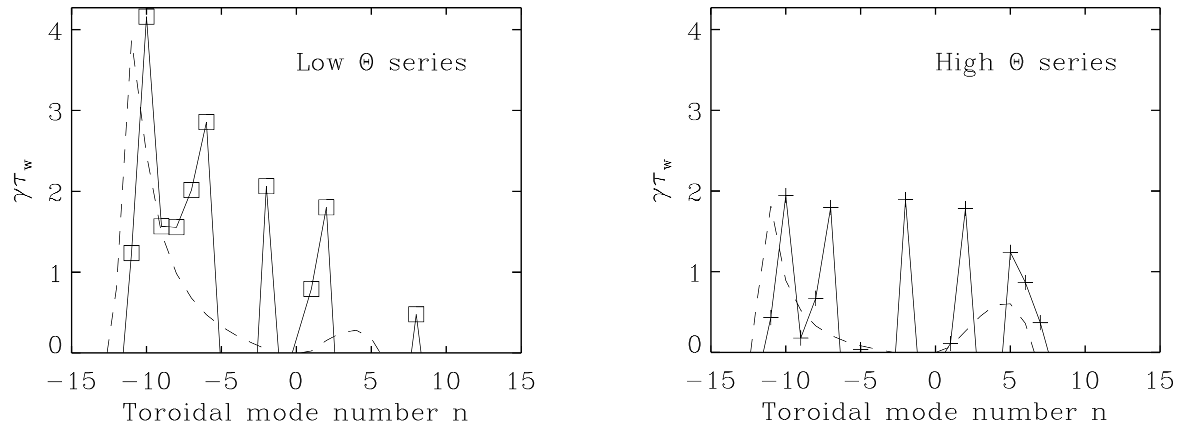

Fig.3. Normalised growth rate $\gamma\tau_w$ versus toroidal mode number n. Linear MHD calculation is compared with experimental estimates. Left is the low-Θ case, right is the high-Θ case.

The mode spectrum is dominated by an internally non-resonant group of *m*=1 modes with toroidal mode numbers *n*=–11 to *n*=–5. Experimentally, the *n*=–10 mode is dominant, with a growth rate of $\gamma\tau_w$=2-4. The internal modes have higher growth rates in the low-*Θ* case than in the high-*Θ* case, in correspondence with linear MHD theory. Low-*n* externally non-resonant *m*=1 modes with toroidal mode numbers *n*=5 to *n*=7 are mainly seen in the high-*Θ* equilibrium. The *n*=5 mode is dominant in this group with a growth rate of $\gamma\tau_w$=0.5-1.5.The growth rates of the external modes are lower than those of the internal modes. This is in agreement with linear MHD theory for the present peaked parallel current density profiles. In general, there is reasonable quantitative agreement with experimental and theoretical growth rates. However, the *m*=1, *n*=–2 mode and the *m*=1, *n*=2 mode could be related to an *n*=2 machine asymmetry due to the two poloidal shell gaps.

Summary

Experimental evidence of internal "on-axis" resistive wall modes in the EXTRAP T2R thin shell RFP have been obtained. The measured growth rates of these internal modes are higher than those of the low-*n* external RWMs. The experimentally measured growth rates for both internal and external RWMs are in reasonable quantitative agreement with linear MHD theory stability calculations. The predominance of the internal modes is due to peaked current density profiles that result in magnetic equilibria close to the ideal MHD stability limit for internal modes.

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